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Landgrebe-Christiansen, Anne; Schunck, Jacob Nørkjær; Popok, Vladimir

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PROPERTIES, CHARACTERIZATION AND APPLICATION OF SEMICONDUCTOR MATERIALS AND STRUCTURES

GRATING-GATE HIGH ELECTRON MOBILITY TRANSISTORS FOR TERAHERTZ MODULATION

A. Landgrebe-Christiansen, J. N. Schunck and V. N. Popok

Department of Materials and Production, Aalborg University, 9220 Aalborg, Denmark
Corresponding author: V. N. Popok (vp@mp.aau.dk)

Terahertz (THz) modulators are required for wireless communication, ultrafast THz interconnects and sensing applications. Great achievements in modulation are reported utilising GaN devices with two-dimensional electron gas (2DEG). In the current work, circular grating-gate transistors based on AlGaN/GaN heterostructures are designed and fabricated. Electrical characterisation of these devices reveals ohmic-like contacts for the source and drain, Schottky barrier for the gate structures and output transistor characteristics confirming the operation through a channel with 2DEG. These circular transistor structures can become a basis for the development of THz modulators where the plasmon polaritons of the grating metal structures will be coupled with the plasmon waves of the 2DEG allowing filtering and modulating THz waves.

Key words: AlGaN/GaN heterostructures; two-dimensional electron gas; high electron mobility transistor.

INTRODUCTION

Use of terahertz (THz) waves is of increasing interest for spectroscopy, detection and imaging in biology, food industry and medicine, communication technologies and security [1–3]. To build THz systems, components enabling to produce, detect, guide and manipulate the THz waves are required. Although, considerable progress in broadband THz generation and detection has been reached [4, 5], techniques to tune properties of THz waves are lagging behind. Among a range of approaches, the plasma wave electronics received a strong boost about two decades ago suggesting GaAs- and GaN-based high electron mobility transistors (HEMTs) with two dimensional electron gas (2DEG) as active THz components [6]. However, fabrication of high-quality devices requires well-developed technologies for the heterostructure growth and component engineering, which have reached maturity only during the last decade. While THz emission, detection and modulation using simple grating-gate and cross-structure 2DEG-based devices were reported a while ago [7], the systems with advanced functional characteristics have been approached only relatively recently.

High efficiency of modulation at sub-THz frequencies has been recently reported using GaAs and GaN devices with 2DEG [8, 9]. However, a weak point of modulators is control of the working frequency. For the tuning, additional frequency selective surface arrays of periodic metallic patches or apertures on a dielectric substrate are typically used [10] increasing complexity of THz systems. An alternative way could be a THz filtering based on

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surface plasmon polaritons of a grating metal structure, which is theoretically suggested in [11]. If such structure is made in the way that it simultaneously serves as a transistor gate, it could be possible to couple the propagating plasmons of the metal structure with the plasmon waves of the 2DEG formed in HEMT, thus, allowing to tune the working frequency by adjusting the configuration of the plasmonic structures.

In the current work, the circular grating-gate HEMTs are designed, fabricated and characterised with the goal to test electronic performance of the devices as a first step in fabrication of THz modulators.

EXPERIMENTAL

In order to use the grating metal structure as a transistor gate, a circular geometry shown in Fig. 1 was suggested. A circular structure, when compared to a square one, allows avoiding an additional insulation between the neighbouring devices. The source of each individual transistor can act as an electrical screening. As can be seen, such design freely allows to vary the dimensions of source, drain and gate electrodes as well as spacing of the grate. Individual circular transistors can also be connected into arrays with common source, drain and gate. Circular structures with different dimensions of electrodes were fabricated. The current paper mostly focuses on the grating-gate systems with $L_G/d = 5/5$ and 30/30 μm.

Fabrication of HEMTs was carried out in collaboration with Twente University (Netherlands). Commercial GaN-on-Si heterostructures with 1.5 μm thick GaN layer, 20 nm thick $Al_{0.2}Ga_{0.8}N$ film and 3 nm thick GaN capping layer were utilised. The source, drain and gate electrodes were fabricated by photolithography patterning. For the gate electrodes, Ni/Au (25/125 nm) metal stacks were formed using e-beam evaporator. To make source and drain electrodes, stacks of Ta/Al/Ta (10/280/20 nm) were deposited and subjected to rapid thermal annealing for 30 s at 550°C in N_2 atmosphere. According to the earlier studies this approach should lead to the formation of ohmic contacts on GaN [12]. Examples of the produced circular grating-gate structures and arrays are shown in Fig. 2.

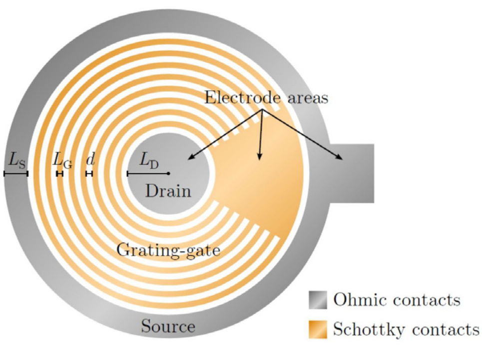

Figure 1. – Schematic illustration of the circular gating-gate design. L_S and L_G are the widths of source and gate electrodes, L_D is the diameter of drain circle and d is the grate spacing

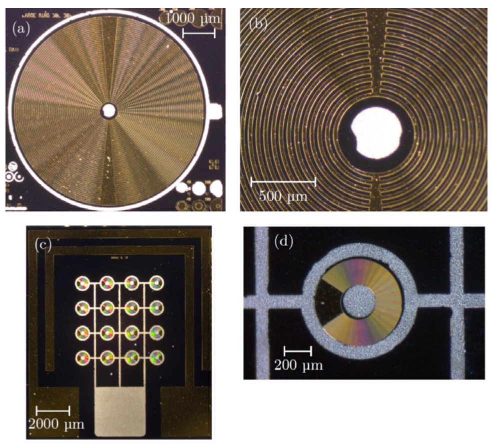

Figure 2. – Optical microscope images of (*a*) grating-gate transistor (L_G/d = 30/30 μm) with (*b*) high magnification of its central part and (*c*) array of structures with (*d*) individual transistor (L_G/d = 3/2 μm)

To check the contact resistance, additional test Ta/Al/Ta structures in shape of stripes (length of 180 and width of 100 μm) with gradually increasing distance between the individual electrodes were fabricated.

The electrical characterisation was carried out by the electrical probe station (SUSS MicroTec) using Keithley 4200A-SCS parameter analyser for applying voltage and measuring current.

RESULTS AND DISCUSSION

Measurements on the test Ta/Al/Ta structures, which should serve as sources and drains, show that a voltage of ca. 1 V is required to get a current between a pair of electrodes. This could be an indication of a small Schottky barrier formation at the metal/GaN interface [13]. Further voltage increase leads to linear current dependence until a saturation due to a limited conductance of the 2DEG channel. The mean contact resistivity of 59 Ohm.mm is found from a series of measurements between different pairs of electrodes. Hence, the contacts are found to be not fully ohmic but ohmic-like.

The *I-V* dependencies for the gate-source and gate-drain electrodes showing a typical Schottky diode characteristics are presented in Fig. 3. The reverse currents saturate at the same value, while in the case of forward bias the saturation currents show a considerable difference, which is most probably related to not perfect ohmic quality of the source and drain electrodes. Very similar *I-V* dependences are obtained on the circular structures with other dimensions.

Fig. 4 one can see the source-drain *I-V* dependences at different gate voltages obtained for the grating-gate HEMT with $L_G/d = 5/5$ μm. Similar to the case of test contact structures, bias of 0.8 V is required to activate the transistor in forward mode. The devise shows good current control by the gate voltage. However, compared to the state-of-the-art HEMTs [14], the dependence of the saturation current on the gate voltage is not linear, which could be an indication of a leakage through the device bulk. Qualitatively the same dependences are observed for the $L_G/d = 30/30$ μm structures.

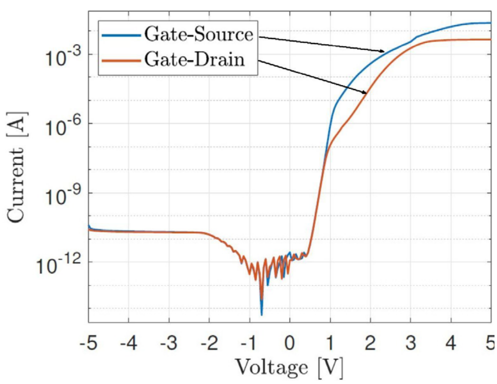

Figure 3. – Gate-source and gate-drain *I-V* dependences for grating gate with $L_G/d = 5/5$ μm

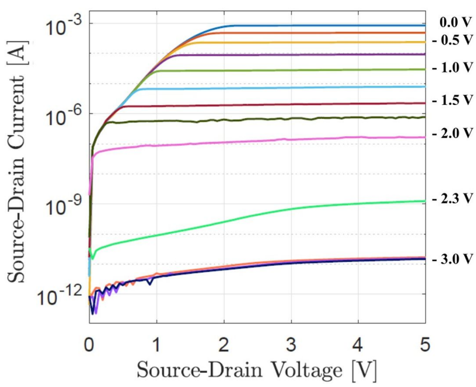

Figure 4. – Gate-source and gate-drain *I-V* dependences for grating gate with $L_G/d = 5/5$ μm

CONCLUSION

The fabricated grating-gate HEMTs with circular geometry show appropriate performance. Although, formation of ohmic contacts and preventing the leakage current require further improvement. Dimensions of the metal grate can be tuned on the micrometre scale without affecting the transistor functional properties, which opens a possibility for the next research step towards investigation of the THz modulation capabilities of the structures with different grating parameters.

REFERENCES

1. Frontiers in terahertz sources and plasmonics / D.M. Mittleman // Nature Photon. – 2013.– V. 7.– P. 666–669.
2. All-integrated terahertz modulators / R. Degl'Innocenti et al. // Nanophoton. – 2018.– V. 7.– P. 127–144.
3. Measurement of piezoelectrically induced charge in GaN/AlGaN heterostructure field-effect transistors / E.T. Yu et al. // Appl. Phys. Lett. – 1997.– V. 71.– P. 2794–2796.
4. THz detectors / F. Sizov, A. Pogalski // Prog. Quantum Electron. – 2010.– V. 34.– P. 278–347.
5. A review of terahertz sources / R.A. Lewis // J. Phys. D: Appl. Phys. – 2014.– V. 47.– 374001.
6. Plasma wave electronics: novel terahertz devices using two dimensional electron fluid / M.I. Dyakonov, M.S. Shur // IEEE Trans. Electron. Dev. – 1996. – V. 43. – P. 1640–1645.
7. High power terahertz emission from a single gate AlGaN/GaN field effect transistor with periodic ohmic contacts for plasmon coupling / T. Onishi, T. Tanigawa, S. Takigawa // Appl. Phys. Lett. – 2010.– V. 97.– 092117.
8. High temperature terahertz detectors realized by a GaN high electron mobility transistor / H.W. Hou et al. // Sci. Rep. – 2017.– V. 7.– 46664.
9. Gbps terahertz external modulator based on a composite metamaterial with a double-channel heterostructure / Y. Zhang et al. // Nano Lett. – 2015.– V. 15.– P. 3501–3506.
10. Progress in frequency selective surface-based smart electromagnetic structures: a critical review / R. Panwar, J.R. Lee // Aerospace Sci. Technol. – 2017.– V. 66. – P. 216–234.
11. Broadband frequency-selective spoof surface plasmon polaritons on ultrathin metallic structure / J.Y. Yin et al. // Sci. Rep. – 2015.– V. 5. –8165.
12. Structure and properties of Ta/Al/Ta and Ti/Al/Ti/Au multilayer metal stacks formed as ohmic contacts on *n*-GaN / I. Boturchuk et al. // J. Mater. Sci.: Mater. Electron. – 2019.– V. 30.– P. 18144-18152.
13. Ohmic contacts to gallium nitride materials / G. Greco, F. Iucolano, F. Roccaforte // Appl. Surf. Sci. – 2016. – V. 383. – P. 324–345.
14. Song, J. Field-effect self-mixing terahertz detectors / Berlin: Springer, 2016.